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THE γ-RAY SOURCE CG 353+16: A SUPERNOVA SHOCK INTERACTING WITH THE CLOUD RHO OPHIUCHI

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ABSTRACT

It is suggested that the *COS B* γ-ray source CG 353+16 may be the result of the acceleration of galactic cosmic rays by an old supernova shock wave and its interaction with the interstellar cloud ρ Ophiuchi. The supernova remnant in question is the North Polar Spur (Loop I). It is proposed that the shock wave of this remnant is in close proximity of the cloud. Cosmic rays are accelerated by the supernova shock in the hot interstellar medium, and the enhanced cosmic ray intensity is "convected" with the shock. When the shock wave has reached the cloud, an unusually high γ-ray emission results. Calculations show that the γ-ray emission by CG 353+16 can be explained quite well by this process if the supernova remnant properties for Loop I inferred from X-ray observations are used.

Subject headings: cosmic rays: general — gamma rays: general — nebulae: individual — nebulae: supernova remnants — particle acceleration — shock waves

I. INTRODUCTION

The *COS B* γ-ray source CG 353+16 (Wills *et al.* 1980) has been associated with the interstellar cloud ρ Ophiuchi, because this cloud is the only obvious feature in the sky at the right location (Mayer-Hasselwander *et al.* 1980). This can be seen from Figure 1 (Plate 7). The measured γ-ray flux is $(1.1\pm0.4)\times10^{-6}$ photons $cm^{-2}\ s^{-1}$ at an energy $E>100$ MeV (Wills *et al.* 1980) which is in agreement with the upper limit of 1.5×10^{-6} photons $cm^{-2}\ s^{-1}$ derived from *SAS 2* (Fichtel *et al.* 1975). The error radius is given as 1°.5 (Hermsen 1980).

The processes leading to γ-ray production by the interaction of cosmic rays with interstellar matter are well known (e.g., Black and Fazio 1973; Bignami *et al.* 1975; Stecker 1977; Fichtel, Simpson, and Thompson 1978; Marscher and Brown 1978). The γ-ray flux from a cloud of mass M (solar masses $M_\odot$) located at a distance r (pc) from the Earth can be calculated using the yield function q_γ (photons/sec/H atom, $E>100$ MeV)

$$F_\gamma(E>100\ \mathrm{MeV})\approx10^{-6}\frac{Mq_\gamma}{r^2}\mathrm{cm}^{-2}\mathrm{s}^{-1}, \qquad (1)$$

where q_γ is expressed in units of 10^{-25}. For a cosmic ray spectrum as observed in the vicinity of our solar system, $q_\gamma\approx2$ (in the above units). The distance estimate for ρ Ophiuchi is $r=160\pm10$ pc (Encrenaz, Falgarone, and Lucas 1975; Whittet 1974) and the mass estimate varies from 2 to $6\times10^3\ M_\odot$ for the clouds within an angular extent of 1°.5, corresponding to a linear dimension of ~4.5 pc (Encrenaz, Falgarone, and Lucas 1975; Vrba 1977). Adopting as a mean value $M=4\times10^3 M_\odot$ we obtain from equation (1)

$$F_\gamma\approx0.31\times10^{-6}\ \mathrm{photons\ cm}^{-2}\ \mathrm{s}^{-1}, \qquad (2)$$

(Note that our chosen value of M is still reasonable even in the light of new column density determinations by Lada and Wilking (1980). The mass of the central region with exceptionally large column density of $\sim3\times10^{23}$ cm^{-2}—possibly a new star forming region—is probably greater than the 450 $M_\odot$ estimate of Myers *et al.* 1978; but since it accounts for only ~10% of the total cloud mass, and large spatial density gradients exist, our adopted value appears reasonable. See also the discussion by Paul, Cassé, and Montmerle 1980). *The γ-ray flux calculated on the basis of these reported mass and distance estimates is a factor ~3 below the measured value, if the cosmic ray intensity at ρ Oph is the same as that in the solar neighborhood.* This would imply that either the distance estimate is too small (by almost a factor 2), the mass estimate is too small (by a factor ~3), or the cosmic ray intensity in the vicinity of ρ Oph is a factor ~3 higher than the intensity in the vicinity of the Sun, or a suitable combination of these three possibilities. This result is different from that obtained by Wolfendale (1980), who used a cloud mass of $\sim 10^4 M_\odot$ and arbitrarily chose the measured γ-ray flux to be 0.7×10^{-6} photons cm^{-2} s^{-1} instead of the reported value.

In this paper we discuss a specific model for enhanced γ-ray emission from ρ Oph. We believe the reported enhancement to be real, i.e., due to an enhanced cosmic ray intensity and not due to uncertainties in the cloud mass estimates or the γ-ray measurements. This model involves the acceleration of galactic cosmic rays by an old supernova shock and its interaction with the cloud. In § II we present observational evidence that such an old supernova shock exists in the vicinity of ρ Oph and that it may indeed interact with the cloud. In § III we briefly summarize the physical processes and constraints of the shock acceleration model for cosmic rays, and show that the properties of the observed supernova remnant are just right. In § IV we calculate the γ-ray emission from ρ Oph based on this model, and in the final section we discuss other models which have been proposed to explain the enhanced γ-ray emission from ρ Oph.

II. OBSERVATIONAL EVIDENCE FOR A SUPERNOVA SHOCK

The shock wave, which we believe may well be responsible ultimately for the anomalously high γ-ray emission from ρ Oph, is the North Polar Spur (Loop I). This is a prominent nonthermal radio feature, and it was suggested as early as 1960 by Hanbury Brown, Davies, and Hazard that Loops I–IV may be old supernova remnants (SNRs; see also the detailed radio studies by Berkhuijsen 1971, 1973). Later X-ray measurements (Bunner *et al.* 1972; de Korte *et al.* 1974; Hayakawa *et al.* 1977; Cruddace *et al.* 1976) confirmed the supernova origin of Loop I.

The neutral hydrogen density determinations within ~100 pc from the Sun, using Lyα absorption measurements (Henry *et al.* 1976), give an anomalously low value—perhaps evidence of a very old supernova cavity with an age of several 10^6 years. The existence of hot plasma supports this idea (Hayakawa *et al.* 1978). Indeed, the shock wave from this supernova may have triggered star formation in ρ Oph. The star forming region in that cloud is also several million years old (Vrba 1977), and thus we have a spatial and temporal association, which may be significant.

The "younger" SNR (Loop I) is expanding in this hot, tenuous background plasma. From X-ray measurements and comparison with the radio shell, Hayakawa *et al.* (1977) arrive at the characteristics shown in Table 1 for the younger SNR which forms Loop I.

Taking the large radius for the SNR of 115 pc implies an interstellar gas density of $\sim 7\times 10^{-3}$ particles cm^{-3},

TABLE 1

CHARACTERISTICS OF LOOP I

Characteristic	Assumed Value
Shock temperature T	$\sim 2\times 10^6$ K
Supernova energy E_{SN}	$\sim 3\times 10^{51}$ ergs
Age of SNR t...............	$\sim 1.1\times 10^5$ years
Distance from the Sun R ...	$\sim 130\pm 75$ pc
Radius of SNR r_s	$\sim 115\pm 65$ pc
Shock speed v_s	$\sim 3.5\times 10^7$ cm s^{-1}
Direction of the center......	$l\approx 329°\pm 1.°5$; $b\approx 17.°5\pm 3°$

not inconsistent with the Lyα measurements. It is clear that large R and r_s must go together. Apparao *et al.* (1979) conclude from *SAS 3* soft X-ray observations that the shock front corresponding to Loop I has not reached ρ Oph (because of the lack of absorption), although it would be more correct to say that the shock front cannot have passed ρ Ophiuchi by a significant distance. Figure 2 shows a possible geometry, well within the measurement constraints, in which the shock wave of Loop I exactly reaches ρ Oph at the present time. The values for R and r_s are 100 pc and 80 pc, respectively, requiring a supernova energy of $\sim 10^{51}$ ergs, an interstellar gas density of 10^{-2} cm^3, and a SNR lifetime of $\sim 10^5$ years, i.e., not too different from the values computed by Hayakawa *et al.* (1977). Tanaka and Bleeker (1977) examine some constraints on the supernova, and our model values are well within the range of possibilities.

III. PHYSICAL PROCESSES

The scenario which we believe is the most likely one to apply to ρ Oph is the following: Ambient cosmic rays

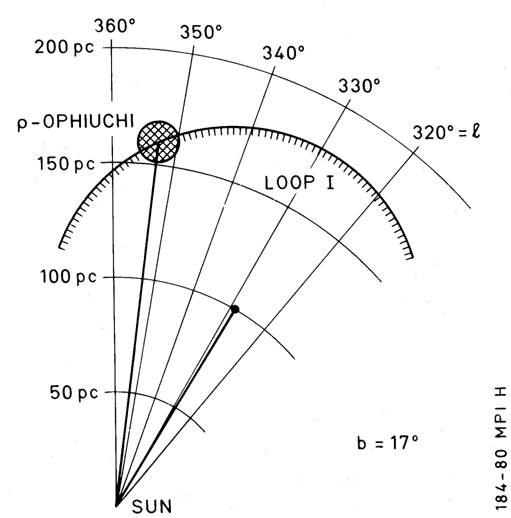

FIG. 2.—Suggested geometry, which is well within the observational constraints, and shows the SNR shock wave of the North Polar Spur (Loop I) interacting with ρ Oph.

are accelerated at the shock wave of a SNR (e.g., Axford, Leer, and Skadron 1977; Krymsky 1977; Bell 1978*a*, *b*; Blandford and Ostriker 1978; see also Scholer and Morfill 1975) while the supernova expands into the hot interstellar medium (HIM). At some stage the shock wave hits the cloud and immerses the cloud in a region of enhanced cosmic ray intensity. Clearly, to illuminate the whole cloud with cosmic rays a large shock front of dimension much greater than the cloud diameter is needed, so that only supernova shocks need be considered. We shall now briefly discuss the various physical processes involved and the constraints which apply before we arrive at our final physical description.

a) *Shock Acceleration in the HIM*

The time asymptotic value for the cosmic ray particle intensity spectrum, using the test particle picture given by, e.g., Axford, Leer, and Skadron 1977, is

$$j_s(p,p_0)=\frac{L}{L-C}j_0\left(\frac{p}{p_0}\right)^{2-3C}\left[1-\frac{C}{L}\left(\frac{p}{p_0}\right)^{-3(L-C)}\right] \tag{3}$$

for $p\geq p_0$, where the ambient cosmic ray intensity is $j_0(p/p_0)^{2-3C}$ at $p\geq p_0$ and $j_0(p/p_0)^2$ at $p\leq p_0$ with $3C=4.6$ from measurements at Earth. The value of the momentum p_0, where the spectrum cuts off at low energies, is difficult to determine from cosmic ray measurements at Earth due to solar modulation. An informed guess is ~ 20 MeV, which corresponds to a momentum of ~ 0.2 GeV/c. The quantity $L\equiv V_s/(V_s-V)$, where V_s denotes the shock speed and V is the plasma velocity behind the shock. For a strong shock we have $L=4/3$. We see then that according to equation (3) the cosmic ray intensity spectrum is changed from a $p^{-2.6}$ to p^{-2} dependence at $p\gg p_0$, i.e., high energy particle fluxes may be significantly enhanced by the shock acceleration.

It is exactly these high energy particles which are mainly responsible for γ-ray production above ~ 100 MeV via the $\pi^0\rightarrow 2\gamma$ decay. Most of the γ-rays are produced from cosmic rays in the momentum range 1 GeV/$c<p<10$ GeV/c, as can be seen (Fig. 3), if we fold the π^0 production cross section times multiplicity with the cosmic ray intensity spectrum (see also, e.g., Stecker 1971). Equation (3) gave the time asymptotic value for the enhanced cosmic ray flux, formally resulting in an infinite cosmic ray energy density for a p^{-2} spectrum. Since a supernova shock evolves with time, we have to determine the limits of validity of using relation (3) in a realistic model, and find the enhancement of the cosmic ray energy density from different arguments. The point is that at any time the energy enhancement, as shown in Figure 3, can only extend to a maximum energy $E_{\max}$.

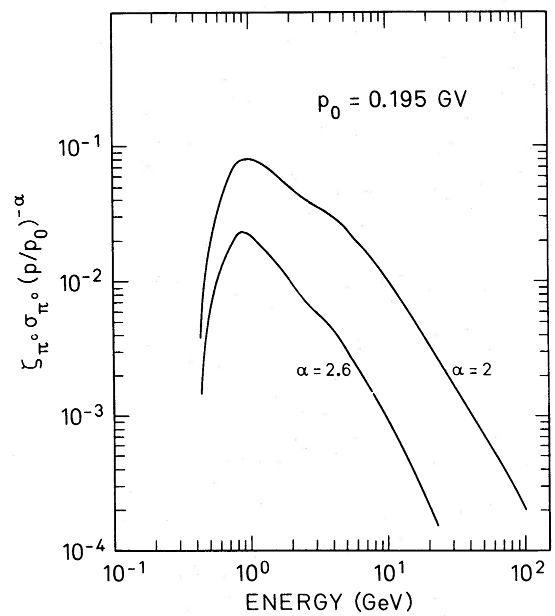

FIG. 3.— The product (π^0 production cross section) $\times$ (multiplicity) $\times (p/p_0)^{-\alpha}$ as a function of energy for protons. The ambient cosmic ray spectrum ($\alpha=2.6$) and a shock accelerated spectrum (high Mach number shock giving $\alpha=2$) are shown. The value of p_0 was chosen as 0.195 GV, which corresponds to an energy of 20 MeV.

b) *Constraints on the Supernova Shock*

The occurrence of shock accelerated cosmic rays in supernova remnants (as well as a certain distance upstream) is discussed by, e.g., Morfill (1981). Here we only summarise the constraints and the energy argument.

The amount of cosmic ray energy added to the remnant in unit time is given by

$$\frac{dE(t)}{dt}=f\varepsilon_{\rm CR}\,4\pi r_s(t)^2 V_s(t)\ \text{ergs s}^{-1}, \tag{4}$$

where $\varepsilon_{\rm CR}\approx 1$ eV cm^{-3} is the background ambient cosmic ray energy density, r_s is the radius of the SNR, and V_s the shock velocity. The factor f is the enhancement factor due to interaction with the shock.

Upstream of the shock, the thermal energy density of the gas, the cosmic ray energy density, and the magnetic energy plus wave energy density are all approximately equal. As a result of the interaction with the shock the gas becomes heated, and the cosmic rays are accelerated and in turn generate MHD turbulence upstream, which is overtaken by the shock and amplified (see e.g. Lerche, 1967; Kulsrud and Pearce 1969; Wentzel 1974; Morfill and Scholer 1977). The MHD waves may become damped (e.g., Lee and Völk 1973; Kulsrud 1978) and contribute to a reheating of the gas inside the remnant. Heat conduction is also important (e.g., Chevalier 1975;

Solinger, Rappaport, and Buff 1975), keeping the gas temperature in the remnant approximately constant throughout. It is a reasonable simplification to assume that the kinetic energy flux of the upstream medium, incident on the SNR, is converted in equal parts into thermal energy, cosmic ray enhancement, and electromagnetic energy. This means that in equation (4) we may write the energy flux

$$f\varepsilon_{\rm CR}V_s \approx \tfrac{1}{3}\left(\tfrac{1}{2}\mu n V_s^{\,3}\right)(1-\eta), \tag{5}$$

where η is the ratio of downstream to upstream kinetic energy flux in the shock frame. For strong shocks $\eta = 1/16$, μ is the mean molecular weight (~1.4 proton masses, if we use a ratio He/H≈0.1), and n is the upstream interstellar gas density.

Particles which are injected into the SNR suffer subsequent adiabatic energy losses. The relationship $Pu^{\gamma}=$ const holds (P=pressure, u=volume of the SNR), and γ equals 5/3 for nonrelativistic particles and 4/3 for relativistic particles. This leads to an energy decrease from E_0 to E, when the volume expands from u_0 to u given by

$$\frac{E}{E_0} = \left(\frac{u_0}{u}\right)^{\gamma-1}. \tag{6}$$

Thus the total cosmic ray energy accumulated in a SNR between the times t_1 and t_2 is given by

$$E_{\rm CR}(t_1, t_2) = \int_{t_1}^{t_2} dt \frac{dE(t)}{dt}\left[\frac{u(t)}{u(t_2)}\right]^{\gamma-1}. \tag{7}$$

Substituting from equations (4) and (5) gives

$$E_{\rm CR}(t_1, t_2) = \frac{2\pi\mu n(1-\eta)}{3\left[r_s(t_2)\right]^{3(\gamma-1)}}\int_{t_1}^{t_2} dt V_s(t)^3 r_s(t)^{3\gamma-1}. \tag{8}$$

Let us assume that the SNR is in a phase where its dynamics can be described by the Sedov (1959) similarity solution, i.e.,

$$r_s = \left(\frac{2E_{\rm SN}}{\mu n}\right)^{1/5} t^{2/5}, \tag{9}$$

where $E_{\rm SN}$ is the supernova energy. Since the energy enhancement in the cosmic rays is largely in relativistic particles, we may take $\gamma=4/3$. Substituting in equation (8) then yields

$$E_{\rm CR}(t_1, t_2) = \frac{\pi}{5}E_{\rm SN}\left[1-\left(\frac{t_1}{t_2}\right)^{2/5}\right]. \tag{10}$$

Thus the total cosmic ray energy content in the SNR is approximately independent of time once $t_2 \gg t_1$. The value of t_1 is ~240 years (Kahn 1975) and is the time scale when the SNR enters the Sedov phase. Furthermore, the energy in the cosmic rays at a late stage is a substantial fraction of the original supernova energy $E_{\rm SN}$. The factor $\pi/5$ given in (10) is too large, because many loss processes (e.g., nuclear collisions, wave generation, synchrotron radiation, etc.) have not been considered; however, most losses can be shown to be small, so that this factor should not be grossly in error. This situation continues until shock acceleration of energetic cosmic rays is no longer possible, at a time t_0, radius r_0, and shock velocity V_0. This limitation occurs because the shock speed must be much larger than the Alfvén speed $v_{\rm A}$ in the HIM, otherwise acceleration is not efficient (Blandford and Ostriker 1978).

Substituting typical values for a supernova of 10^{51} ergs expanding into the HIM (density $\sim 10^{-2}$ cm^{-3}), one obtains an "active" supernova lifetime, where the cosmic ray energy density averaged over the remnant is at least 3 times the "local" value in the vicinity of the Sun, of

$$t_{\rm active} \approx 2\times 10^5 \text{ years}. \tag{11}$$

Thus it appears that the derived properties of the North Polar Spur (§ II) are quite appropriate; and if the shock has reached ρ Oph or has already swept over it some distance, then the cosmic ray flux in the vicinity of the cloud must be significantly enhanced relative to the value in the vicinity of the solar system. The probability that a SNR should interact with a cloud in the way envisaged here increases with remnant size. Thus the late "active" stages with relatively modest cosmic ray enhancement are of considerable interest in the context of γ-ray sources (Morfill 1981).

VI. γ-RAY EMISSION FROM ρ OPHIUCHI

According to the model which we have developed in §§ II and III, ρ Oph is surrounded by an enhanced cosmic ray flux, which is to a large extent simply convected into the cloud. This is shown schematically in Figure 4. It is assumed that the cosmic rays convect with a velocity V_2=plasma velocity towards the cloud and that the flow pattern around the cloud is such that a convection velocity V_1 establishes itself behind the cloud. The cloud's spatial extension is represented by a δ-function with column density $L_c n_c$ (L_c=dimension of the cloud, n_c=mean gas density in the cloud) as far as the cosmic rays are concerned.

The reason is that inside the cloud any waves which could resonantly interact with cosmic rays and scatter them are damped away by ion-neutral friction so that cosmic rays in clouds move with their own distinct speed (~ speed of light). Thus the time spent inside a

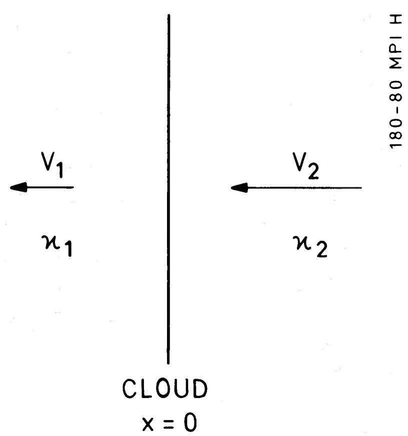

FIG. 4.—Schematic diagram showing the geometry as "seen" by the cosmic rays. The SNR plasma convects against the cloud with velocity V_2. Downstream the velocity is $V_1 \leq V_2$ (see text). The cloud appears as a δ-function with a given column density $n_c L_c$.

cloud is short compared with the other time scales in the problem and the δ-function representation appears reasonable (Völk, Morfill, and Forman 1981).

The flow topology shown in Figure 4 is, of course, very much simplified, although some support of our model can be obtained from the numerical work of Woodward (1976). The two extreme cases which must be compared are $V_1 = V_2$, which corresponds to the establishment of the same flow velocity relatively quickly behind the cloud, and $V_1 < V_2$, which corresponds to the situation where the shock has not completely engulfed the cloud and the turbulent wake behind the cloud which has no net directed plasma velocity over a large distance. In the latter case $V_1 \sim v_A$, the speed of the cosmic ray scattering centers. Since $v_A \ll V_2$, we may put $V_1 \sim 0$.

The requirement for this latter description to be applicable for *all* shock cloud collisions is that the length of the turbulent wake L_w, which is produced, should be so great that the shock wave takes longer than the canonical time of $\sim 2 \times 10^5$ years (see § III) to cross it, i.e., in the case of ρ Oph, where the shock is believed to hit the cloud after $\sim 10^5$ years, we would require

$$L_w > 25 \text{ pc}. \tag{12}$$

For a cloud of the dimension of ρ Ophiuchi ($L_c \approx 4.5$ pc) this implies a ratio $L_w / L_c \approx 5$ which seems feasible. In other words, for the time scales of interest the shock has probably not completely engulfed the cloud and has not reformed as a continuous structure behind it.

Generally, the equations which govern the transport of cosmic rays in the model described are:

$$\text{region 1:} \quad \frac{\partial}{\partial x}\left(-V_1 F_1 - \kappa_1 \frac{\partial F_1}{\partial x}\right) = 0, \tag{13}$$

$$\text{region 2:} \quad \frac{\partial}{\partial x}\left(-V_2 F_2 - \kappa_2 \frac{\partial F_2}{\partial x}\right) = 0, \tag{14}$$

with the conditions:

$$\text{at } x = -\infty,\ F_1 = \text{const},$$

$$\text{at } x = 0,\ F_1 = F_2 \equiv F_c;$$

and the streaming condition

$$\left[-V_1 C_g F_1 - \kappa_1 \frac{\partial F_1}{\partial x}\right]_{x=-0} + \left[V_2 C_g F_2 + \kappa_2 \frac{\partial F_2}{\partial x}\right]_{x=+0} = \frac{L_c}{\tau} F_c, \tag{15}$$

where $C_g \equiv -\frac{1}{3} p \partial / \partial p$ is the Compton-Getting operator. It is easy to show that the cosmic ray flux in the cloud, F_c, is given by

$$F_c = F_s \left[1 + \frac{L_c}{\tau V_2} - \frac{C(V_2 - V_1)}{\tau V_2}\right]^{-1}, \tag{16}$$

where F_s is the cosmic ray flux at $+\infty$, i.e., the incident flux which is enhanced inside the SNR. The value of C, if the SNR shock is sufficiently strong, is 4/3. We see from (16) that in the two cases discussed above, we get

$$1)\ V_1 = V_2 : F_c = F_s \Big/ \left(1 + \frac{L_c}{\tau V_2}\right); \tag{17}$$

$$2)\ V_1 = 0 : F_c = F_s \Big/ \left(1 + \frac{L_c}{\tau V_2} - C\right). \tag{18}$$

Equation (17) tells us that the presence of the cloud always decreases the cosmic ray intensity, because the transport (convection into and away from the cloud) is the same in regions 1 and 2.

Equation (18) tells us that the presence of the cloud may enhance or decrease the cosmic ray intensity. Since with $V_1 = 0$, it is now possible for the cloud to "sweep up" cosmic rays (convection away from the cloud does not exist) and if the losses in the cloud are sufficiently small, this sweeping up may be more important than the losses.

We may now substitute the values appropriate to ρ Oph, i.e., $M \approx 4 \times 10^3\ M_\odot$, $L_c \approx 4.5$ pc $= 1.3 \times 10^{19}$ cm (for a spherical cloud and a mean molecular weight $\mu = 2.4 \times 10^{-24}$ g this gives a mean atom density $n_c = 3.3 \times 10^3$ cm^3), and the gas speed behind the shock $V_2 = \frac{3}{4} V_s \approx 260$ km s^{-1}. The loss time for nuclear collisions is $\tau \approx 1.3 \times 10^{15} / n_c$. Thus we get

$$\tau V_2 / L_c \approx 0.77. \tag{19}$$

The mean column density for ρ Oph which these parameters yield is $\sim 4.4\times 10^{22}$ cm^{-2}. From equation (17) we obtain

$$F_c \approx 0.43 F_s; \quad (20)$$

and from equation (18) we get

$$F_c \approx 1.03 F_s. \quad (21)$$

The cosmic ray flux F_s inside the SNR is enhanced. The enhancement factor can be obtained from equation (10). For a supernova as described in § II ($E_{SN}=10^{51}$ ergs, $n=10^{-2}$ cm^{-3}, $t=10^5$ years) the cosmic ray enhancement is a factor 8, with respect to the value in the vicinity of the solar system. This is in good agreement with the results of Figure 3. Thus the computed γ-ray enhancement due to the shock-accelerated cosmic ray intensity in the SNR of the North Polar Spur (Loop I) —if the shock has really reached ρ Oph—is

$$3.5 < \gamma\text{-enhancement} < 8, \quad (22)$$

where we have assumed that the enhancement in the cosmic ray energy density is all in relativistic particles. Some of the energy enhancement appears in particles below ~0.5 GeV or $p_\pi \approx 1.09$ GeV/c where π^0 production is negligible (see Fig. 3). This amounts to a reduction factor $(1-\xi)$ for the energy enhancement available for γ-ray production, where ξ is given approximately by

$$\xi \equiv \frac{\ln(p_\pi/P_0)}{\ln(P_{max}/p_0)}.$$

It has been assumed that the cosmic ray spectrum takes its asymptotic form $(P/P_0)^{-2}$ up to a maximum momentum, P_{max}, which can be accelerated in the available time. The time scale for shock acceleration has been calculated by Krymsky *et al.* (1978) and Forman and Morfill (1979) and is given by $t_{acc}=4\kappa/v_s^{\,2}$. The size of the diffusion coefficient κ is not known and may be determined by self-generated waves and wave damping processes. Using as an example $P_0=0.2$ GeV/c, and $P_{max}=10$–100 GeV/c, we get $\xi \sim 0.3$. This result is not very sensitive as regards the exact value of P_{max}, so that we get a modified enhancement

$$2.5 < \gamma\text{-enhancement} < 5.6 \quad (23)$$

which is in very good agreement with the observations (Wills *et al.* 1980).

We should like to point out, finally, that the enhancement given by inequality (23) was calculated using the measured (and inferred) parameters applicable to the SNR associated with the North Polar Spur, and the cloud ρ Oph itself. No "adjustment" of the parameters is necessary, and the only requirement is that the shock wave of the SNR has reached the cloud.

V. DISCUSSION

Other possibilities to explain the anomalously high γ-ray emission from ρ Oph have been discussed recently. The most notable suggestion has been that stellar wind terminal shocks from young stars in and near the ρ Oph cloud can accelerate stellar flare particles to relativistic energies and enhance the ambient cosmic ray flux sufficiently to account for the enhanced γ-ray emission (Cassé and Paul 1980; Paul, Cassé, and Montmerle 1980). This argument was based on the fact that mechanical energy is available to accelerate cosmic rays. The acceleration mechanism has been discussed by Jokipii (1968). This model, in its original form, depended on the existence of at last one OB star with a strong stellar wind in the immediate neighbourhood of ρ Oph. Such a star does not appear to exist according to a new analysis by Paul, Cassé, and Montmerle (1980), who then suggested an alternative of many weak wind sources, like T Tauri stars, which can also provide the necessary hydrodynamical energy.

The main problem with the stellar wind model is the fact that a detailed discussion of the physical processes has not been made so far. Of particular importance is the problem of cosmic ray acceleration in the presence of losses (see, e.g., Völk, Morfill, and Forman 1981), the conversion efficiency of the available mechanical energy into other forms and geometrical effects of the cosmic ray distribution inside the cloud. These questions will be discussed elsewhere (Völk and Forman 1981).

The suggestion advanced here, namely that a large shock front belonging to an old SNR is very close to or even in contact with ρ Ophiuchi, receives some support from recent X-ray measurements and offers a natural interpretation of the γ-ray observations.

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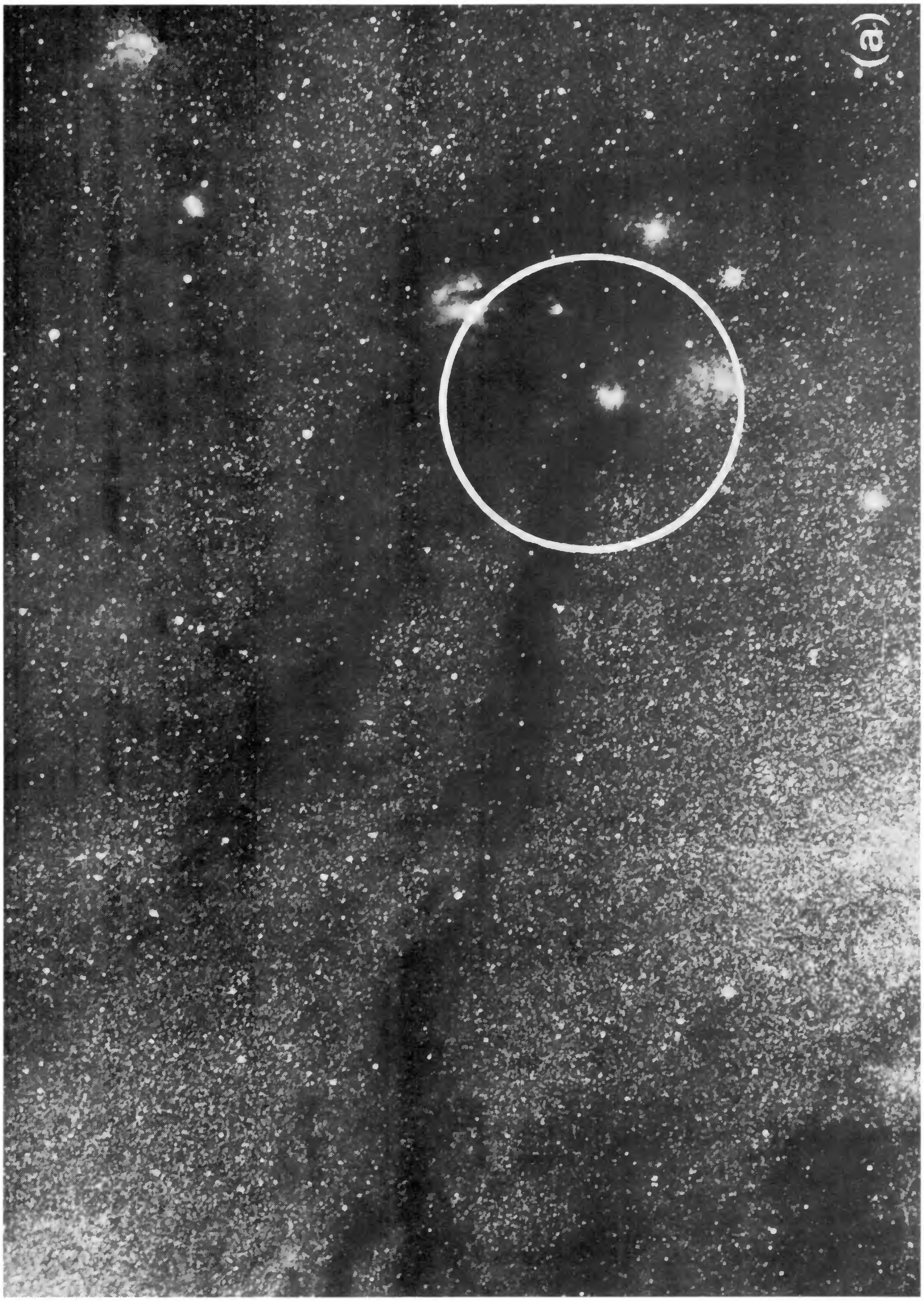

FIG. 1.—A photograph of the ρ Oph cloud (taken from Turon and Menessier 1975) showing also the error circle of the *COS B* γ-ray source CG 353+16.

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